Towards a 10 nm Run-out Rotation axis

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Abstract

A 10 manometer precision rotation axis, or "Nanospindle", is currently being developed to be used on the ultra-high resolution Macromolecular Crystallography beamlines at the ESRF.

Since the best air bearing rotation tables available on the market guarantee an eccentricity in the 50 nm, with a wobble in the microradian range, a second stage including a real time feedback system must be added to reach the requested ultimate precision. The maximum expected rotation speed is limited to 500 rpm. The feedback system is based on a capacitive sensor spindle error analyser (Lion Precision), a Digital Signal Processor (Sheldon Instruments) and two piezoelectric actuator assemblies (Jena Piezosystem). In a first phase, the prototype is being fully characterized at the Precision Engineering Lab, where its stability, together with sensitivity to vibrations and temperature will be assessed. The Nanospindle will then be exported to ID23 where it will be tested in real operating conditions for Multiple Anomalous Diffraction (MAD) experiments.

The principle of operation of the Nanospindle, its design and some preliminary results of the tests on the prototype will be presented.

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1. Introduction

The commercially available air bearing rotary stages offer characteristics that, even if they are excellent, are still insufficient to meet the current requests by the Biology community for very high resolution notably for the Multiple Anomalous Diffraction (MAD) experiments on macromolecules (mainly proteins).

The problem will be even more severe on nanotomography experiments. Here the goal is to reach 10 nm lateral resolution over a full revolution of the sample in the beam in order to avoid any blurring of the images after reconstruction of the tomographic pictures. Facing that problem, we have decided to build an instrument which would compensate in real time the still existing eccentricity and wobble on a commercially available air bearing rotary stage, with the ambitious goal of reaching the imposed 10 nm maximum eccentricity. As in any other regulation chain operating in closed loop, our instrument includes a device that measures the main shaft position, a programmable electronic circuitry that amplifies the positioning error and sends an appropriate control voltage to the shaft re-positioning devices.

The eccentricity is however not the only important parameter to be controlled. Its reduction must also be accompanied by a strict control of the wobble also present in the standard, high quality, air bearing rotation stages. The goal here is to get images of real tomographic planes and not of cones after re-construction of the projections.

The maximum speed of rotation, linked to the detector acquisition speeds, is limited to 500 rpm in our present device.

2. Commercially available air bearing rotary stages

The key component in the new instrument is the air bearing rotary stage, since it will support the whole rotating assembly. It was therefore important to confirm the characteristics announced by the different manufacturers at the time of the purchase. The measurements performed at the ESRF Precision Engineering Laboratory indicated that both the eccentricity and the wobble were 5 to 10 times larger than the values specified by the manufacturers (25 to 250 nm eccentricity; 0.1 to 2.5 μrad wobble without motor for the best units which makes them useless for our application). Finally, after the intervention of the manufacturer on one of the rotary axis available at the ESRF (Aerotech ABR 1000) [1], these values were reduced to twice the specified value. A final wobble value of 12 μrad was measured. It was then decided that this latest value would be acceptable for our application since it would be keeping the main rotary shaft within the re-positioning range of our actuators.

3. Principle of operation

Two identical assemblies of two stainless steel flexors, 1.5 mm thick, support the main shaft on the air bearing rotary table (Aerotech ABR 1000).

The accurate re-positioning of the shaft in the centre of the air bearing rotary table axis is determined by the piezo-actuators (Jena Piezosystem P8/10) [2] which move the shaft against a pair of spring-loaded pushers. The maximum stroke of these actuators is 8 μm. The two assemblies supports the shaft by the two opposite sides of the air bearing rotary table, in order to compensate for any eccentricity but also any wobble within the stroke of the actuators (linear and angular positioning).

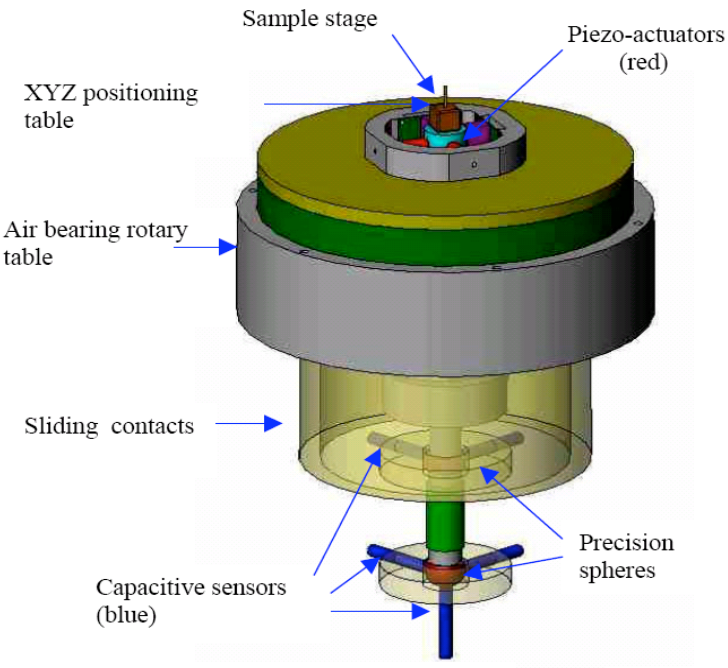

Fig 1: Principle of operation

A set of 5 capacitive sensors (resolution in the order of 1 nm) measures the instantaneous positions of two reference balls mounted on the main shaft. The capacitive sensors and the balls are part of a Spindle Error Analyser (SEA) developed by Lion Precision and IBS [3] for testing high accuracy spindles. Four sensors measure the radial and angular displacements, whilst the fifth one measures the axial movement of the shaft. It is obviously essential to support these sensors with a maximum of mechanical and thermal stability since, like the reference balls, they will be the final reference points for the whole s
sembly.

The signals generated by the sensor amplifiers will input a Digital Signal Processor (DSP) from Sheldon Instruments [4], which will control the piezoelectric actuators in function of the angular position of the rotary stage. Since all the actuators rotate with the shaft, their voltage controls are conveyed through a sliding contact assembly (slip ring) custom made by Fabricast.

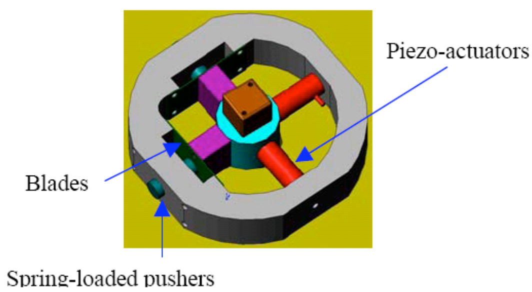

Fig 2: Principle of operation: detail.

The specially developed control software generates the compensation signal that is applied to the piezoactuators through their high voltage controllers.

The XYZ positioning table at the top of the instrument is used to re-position the region of interest of the sample in the accurate axis of rotation determined by the whole assembly. The Z channel however is linked to the fifth sensor at the bottom of the assembly, and will compensate for possible axial displacements.

4. Construction details

The “Nanospindle” design details are shown in the Autocad drawing of Fig 3. As already stated, a particular attention was paid to the mechanical and thermal stabilities in supporting the capacitive sensors and reference balls. To this end, the whole assembly will be mounted on an active anti-vibration table made of a granite table resting on three damping legs (Bilz) [5], with a guaranteed eigenfrequency below 1.1 Hz, an no amplification of the ground vibration below 1 Hz. The attenuation provided by the anti-vibration system at all frequencies above 10 Hz is larger than 10 dB.

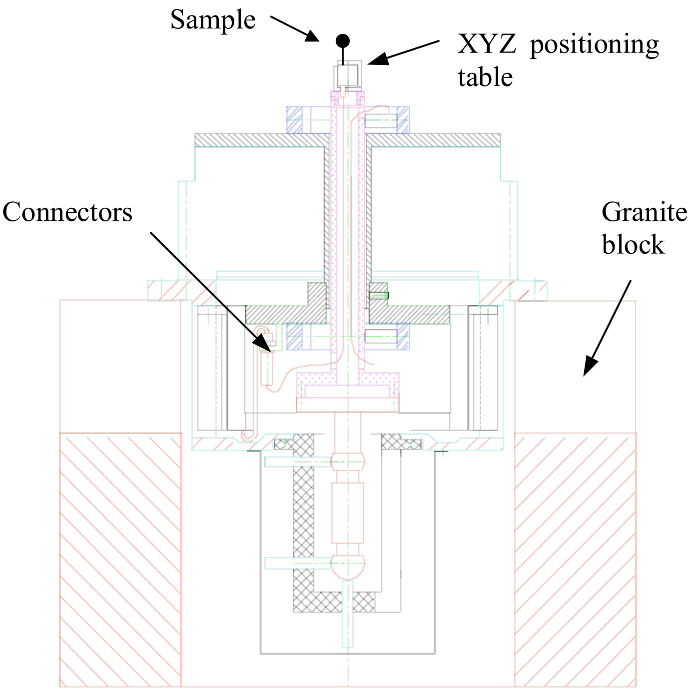

Fig 3: Construction details.

For the same reason, a drilled granite block supports the air bearing rotary stage, which itself supports the sensor assembly via a cylinder made of synthetic granite (not shown on the drawing).
To guarantee a good thermal stability, the main shaft and the capacitive sensor supports are made of Super-Invar.
The cables supplying the piezoactuator control voltages at the top of the assembly are led through an axial hole going through the main shaft from the bottom of the instrument. The cables can be disconnected from the slip ring assembly thanks to high quality connectors Lemo [6]. A disk plate that also rotates with the assembly supports the connectors.
For testing purpose during the characterization procedure, the top of the main shaft supporting the XYZ positioning table is removable and can be replaced by another precision ball assembly, part of a second SEA.
All the mechanical linear and angular tolerances concerning the parts in motion are extremely tight to ensure that the manufacturing and assembling errors are within the stroke of the piezoactuators.

5. Control principle

The control system is based on the real-time control board from Sheldon Instruments with Digital Signal Processor (DSP), (ref: C6713 with 1800MFLOPS peak performance) and input/output converters with 100kHz sampling rate, capable of operating the rotary stage at its maximum speed of 500rpm. The board is inserted in a standard PC as a PCI card and can be easily configured and adjusted during the operation. The values are input to the controller through a Graphical User Interface (GUI) based on the well know LabView environment.

The control system can be divided into two parts:

- **The real time operating system** runs directly on the DSP and simultaneously executes the program of the programmed controllers. The eccentricity and wobble of the shaft are measured with respect to the reference axis of the system determined by the granite table. The actuators are mounted on the rotating part of the stage and their actuation is corresponding to the relative axis of the rotating table. The program has to mathematically transform the measured position errors with respect to the reference axis into the current relative angular position. The generated error signals are used to control the actuators. The fifth vertical sensor directly controls the axial position using the Z motion of the Minitritor XYZ positioning table.

- **The user interface** has two main functionalities. It displays the actual eccentricity, wobble and position of the XYZ positioning table and it also provides the possibility of directly commanding the Minitritor positioning table. All parameters of the shaft position controllers can be as well adjusted according to the specific mode of operation (step operation or continuous rotation) and to the user needs.

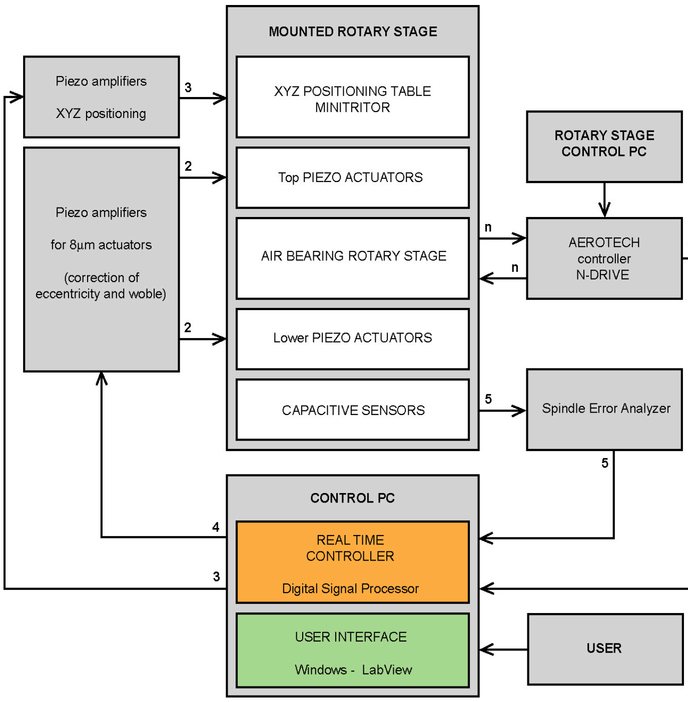

Fig 4: Fully mounted system.

The operation of the entire system can be shortly described according to the figure 4. The Lion Spindle error analyzer provides the measured position of the shaft as analog value for each capacitive sensor to the controllers input converters. The rotary stage angular position is the additional information necessary to generate the actuation signals. The measured position of the shaft is numerically transformed from the reference axis to the relative ones as a function of the angular position. These relative capacitive sensor positions have to be further transformed into a real position of the sample that is mounted at the opposite end of the shaft. These values are fed into the set of PID controllers driving four piezoactuators mounted on the rotary stage. Three driving signals for the Minitritor are provided according to the values set by the users.

6. Integration on a Macromolecular Crystallography beamline.

After its full characterization, the “Nanospindle” will be transferred to one of the ESRF Macromolecular Crystallography (MX) beamlines, namely ID23-2 where Multiple Anomalous Diffraction scattering experiments are conducted. The Fig 5 illustrates the final environment in which the “Nanospindle” will be integrated. The operating conditions at that beamline, as at any other MX beamline at the ESRF, are largely different from the PEL ones. Three main problems will have to be overcome.
The first one will deeply modify the concept since the axis of rotation will have to be oriented horizontally. In the new concept, the two reference balls will be separated and located at both sides

of the rotary stage to compensate for the gravity-induced bending of the shaft. An active correction of the axial errors will be added.

The second main problem will be the thermal stability in the experimental hutch and around the sample in particular. During all MX experiments the samples are kept under 100 K by a cryostream of evaporating liquid nitrogen directed directly to the sample. This will obviously disturb the thermal stability and create turbulences in the sample vicinity. Several paths are currently being investigated to solve that problem.

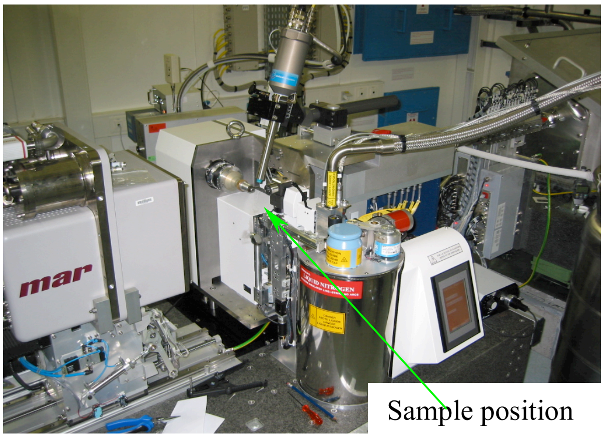

Fig 5. Sample environment at the beamline

The third source of difficulties is the vibration level on the experimental set-up since no anti-vibration system is foreseen at the moment.

The reshaping of the "Nanospindle" will offer the opportunity of reducing its current size.

Other standard components could most probably be selected to take all these imposed modifications into account.

7. Conclusions

The goal of the development of the current "Nanospindle" prototype is to validate its concept together with its components. It cannot be used as it is for synchrotron radiation experiments other than nanotomography. Some components are not optimised; for example the rotary stage clearance diameter is very small and limits the diameter, and hence the stiffness, of the main shaft.

It is being tested at the ESRF Precision Engineering Lab in thermally stable conditions (the temperature is controlled within 0.3 degree) and on an active anti-vibration granite table. At the time of writing this report the characterization and qualification of the standard components and of the measuring devices is completed, and the digital signal processor is being programmed. However, the "Nanospindle" is not fully assembled yet. The final tests should be completed this year.

After its validation, the prototype will be modified and adapted to the MX beamline working conditions that are much less favourable for reaching ultimate eccentricity and wobble as compared to the PEL conditions. The necessary modification will have to be introduced to cope with these new conditions. Amongst the difficulties linked to the real conditions of use, we may cite: imposition of the horizontal axis of rotation, thermal variations and air turbulences, vibrations induced by the floor but also by the technical environment,…

The new instrument will also be made more compact to be integrated in other nano-positioning devices (mainly one-, two- or three-axis linear translations) that are also under development at the ESRF.

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References

[1] Aerotech, Inc., 101 Zeta Drive, Pittsburgh, PA, USA

[2] Piezosystem Jena GmbH, Pruessingstrasse 27, D-07745 Jena, Germany

[3] Lion Precision / IBS Precision Engineering bv, Esp 201, 5633 AD Eindhoven, The Netherlands

[4] Sheldon Instruments, Inc., 609 West Date Street, San Diego, CA., USA

[5] Bilz Vibration Technology AG, Böblinger Strasse 25, D-71229 Leonberg, Germany

[6] LEMO S.A., Chemin de Champs-Courbes 28, P.O. Box 194, CH-1024 Ecublens, Switzerland